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LIBERATION OF NUCLEAR ENERGY

Ya. I. Frenkel'
Acad Sci USSR

/The book Liberation of Nuclear Energy, written by one of Russia's greatest nuclear physicists, corresponds to the Smyth Report and may be termed the Russian "Frenkel'" Report. It is quite elementary and historical, and is designed for lay and nonscientific readers startled by the appearance of the atomic bomb over Hiroshima. It was written before the Smyth Report, whose appearance caused only a few minor changes in the final publishing. The table of contents, author's foreword, and Section 26, "Nuclear Reactions in Technology," follow./

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PREFACE

The explosions of the atomic bombs over Hiroshima and Nagasaki naturally created a sensation; but their greatest effects were felt in engineering and technical circles concerned with the question of nuclear energy. Lying dormant until that moment within heavy atoms, but occasionally escaping from the heaviest atoms as natural radioactivity, this energy was at last set free by man. Now the problem is to harness it to work for the good of mankind.

Interest in the sensational appearance of nuclear energy on the stage of the Far East theater of war must give way to a more peaceful thirst for knowledge, a deeper study of atomic structure (or more accurately, of atomic nuclei), the concentration of the energy under discussion, and the nuclear processes under which it is liberated.

The essence of this problem can be expressed in a few lines.

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The lightest atom, hydrogen, consists of a positively charged particle, the proton, which is the simplest atomic nucleus, and a negatively charged electron. The heavier atoms consist of, or more accurately, can be made up of, several hydrogen atoms, as the English scientist Prout suggested a hundred years ago. Moreover, part of the electrons form the light electronic envelope around the atom, while the rest form part of the heavy, but extremely small, positively charged nucleus. In this nucleus the electrons no longer exist in the form of independent particles; instead, they are united with some of the protons to form the neutral particles called neutrons. When hydrogen atoms unite to form more complicated atoms or are annexed to similar atoms, tremendous energy is given off, approximately a million times greater than the energy liberated in ordinary chemical reaction such as in the union of two atoms of hydrogen to form a molecule of hydrogen. In other words, the energy liberated in converting one gram of hydrogen into one gram of a heavier element, helium for example, is approximately equal to the energy set free in the chemical union of one ton of atomic hydrogen to form molecular hydrogen.

The processes of converting hydrogen into heavier atoms take place only at very high temperatures, tens of millions of degrees, which until now were unattainable on the earth and were reached only in the interior of stars due to compression by gravity. The energy radiated from the surface of the sun and other stars in the form of light is the energy liberated in the depths of these incandescent balls of gas due to the conversion of hydrogen into heavier elements. Up to the present, therefore, we have been passive witnesses to distant nuclear processes on a grand scale, which have revealed nothing of their nature, although our very existence on earth has depended upon them.

During the transmutation of hydrogen atoms into heavier atoms in the interior of the sun and stars, nuclear energy is radiated in powerful outward streams. Under such conditions can one speak of its "accumulation" in the complicated atoms formed thereby? Are not these heavy complicated atoms the tombs of atomic energy rather than their sources?

Indeed, comparatively light elements with atomic weights up to 100 - 150 are similar "tombs," i.e., incapable of further release of energy. Heavier elements, however, in spite of the fact that great amounts of energy have already been liberated from them during their formation from hydrogen, can still serve as sources of somewhat lesser, though still titanic energy by dividing their nuclei into two daughter (complex) nuclei, roughly equal in size. This circumstance, dependent upon the powerful forces of nuclear attraction binding protons and neutrons in heavy nuclei, is resisted by the forces of electric repulsion between positively charged protons. When the number of the latter increases, these forces, striving to split the atomic nucleus, grow more rapidly than the nuclear forces of cohesion. That is why the heavy nuclei are metastable, i.e., only comparatively stable, for with a small expenditure of energy to overcome their stability, they disintegrate or divide. This process of diversion or disintegration into smaller nuclei is accompanied by the liberation of a titanic amount of "sub-atomic" energy, incomparably greater than the energy spent in the process of liberation.

In the case of heavier elements, the energy required to disintegrate the nucleus into a light helium nucleus and a residual heavy nucleus, or into two daughter nuclei of approximately equal size, is so small in comparison that the nuclei of these elements are themselves disintegrated. But this disintegration constitutes in part the essence of the phenomenon of radioactivity. These heavy elements are found in the earth only in very small sizes, such as those of grains. Radioactivity takes place in them extremely slowly -- too slowly to have technical significance. Elements heavier than uranium, the transuranic elements, do not exist under natural conditions because they would have too little stability and would disintegrate too rapidly.

Modern nuclear physics enables artificial production of transuranium elements which should follow immediately after uranium in Mendeleyev's periodic system, neptunium (No 93) and plutonium (No 94). (Recently, according to a communication from an American physicist, Sieborg, two new elements have been added to it: No 95, called "Americium" and No 96, "Curium." This note was added during revision.) It has proved possible to obtain plutonium in sufficient quantities for use as the explosive in atomic bombs.

Such a primary explosive may be provided by a light isotope of uranium (the so-called actinouranium or radiouranium) as well as by plutonium, if it is isolated in pure form and in sufficiently large quantities. Moreover, in both cases the explosion may be brought about without a preliminary rise in temperature by the rapid multiplication of neutrons which cause the fission of the plutonium or actinouranium nuclei, and in turn develop a double or triple number of neutrons at each fission ("chain explosion").

In this book, I did not attempt to examine in detail the technical problems in the manufacture of atomic bombs. But the experimental facts and theoretical principles which form the basis for this new and amazing achievement of modern engineering cannot be secret since they were already established in 1941 and have been widely published in the scientific press, including the Soviet. I shall try to familiarize the reader with these facts and principles without assuming that he has any special training beyond the general knowledge acquired from intermediate schools. The first chapter will serve as an introduction presented in simple form. I have not gone into the details of experimental methods in nuclear physics, but have restricted myself to a short exposition of their nature so that the reader can form for himself a picture of the manner in which the facts and principles set forth were established. -- Leningrad, October 1945.

Section 26. NUCLEAR REACTIONS IN TECHNOLOGY

(Author's Note: This section was revised somewhat after the appearance of the Smyth Report, but the necessary revisions were made during proofreading.)

In the preceding sections we have already touched upon two technological applications of present-day nuclear physics: (1) the production of artificial radioactive elements with any desired chemical properties and in any quantity necessary for the practical needs of chemical analysis (radioactive indicators) and of medicine (radiotherapy); and (2) the creation of the atomic bomb.

Turning to the latter problem, we shall first summarize the most likely methods of effecting nuclear explosions of unstable or, more exactly, metastable heavy elements. The problem is to find that unknown quantity of energy of activation which must be applied to the nucleus to induce it to divide almost instantaneously. Although this energy is small in comparison with that given in fission, it is still very large in comparison with all those energies which can be obtained in ordinary chemical processes (for example, in the explosion of an ordinary chemical explosive). In the case of uranium and plutonium this energy is measured in several meV, which corresponds to a temperature of explosion of the order of one billion degrees centigrade.

Under such demands (tremendous temperatures), the only possible method of bringing about a nuclear explosion at initially comparatively low temperatures is to use the previously mentioned mechanism of chain reaction to split radioactive uranium, or plutonium, in connection with the process of multiplication of free neutrons.

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To set off this reaction, the bombardment of the corresponding target of a metastable heavy element by means of free neutrons from an external source is not necessary; it is possible to utilize "primary" neutrons released in the spontaneous fission of the radioactive uranium or plutonium nucleus. This process proceeds at first slowly, especially in the case of radioactive uranium (radiouranium). Only under favorable conditions will the uranium gradually be driven asunder and finally be able to explode.

To effect an explosion of radiouranium there is no need to separate the radiouranium from the ordinary uranium into its pure form. It is sufficient to enrich the uranium with its light isotope by increasing the content of the light isotope radiouranium over the ordinary uranium only a few fold. But this by no means fully solves the problem. To increase the effectiveness of the fast secondary neutrons, it is necessary to slow them down with the aid of heavy hydrogen or carbon (graphite). It seems then that the neutrons with energy approximately 25 eV are captured by the heavy isotope of uranium, with extraordinarily great force. It is this circumstance that particularly makes necessary the enriching of uranium with the light isotope to effect the chain explosion.

Several years ago American scientists succeeded in obtaining this enrichment as described and also in fully isolating radiouranium with the aid of various methods, very well known in principle, which were brought to a high state of technical perfection. Thus, for example, Urey effected isolation by diffusing one of the gaseous compounds of uranium through porous membranes (the number of these membranes reached 4,000 and their average area was 20 hectares). Lawrence, however, used a method of electromagnetic separation of isotopes, succeeding in effecting the complete separation of both of the isotopes of uranium and moreover in supplying the quantity necessary for technical needs.

To realize the process of chain fission of radiouranium in small quantities, it would be necessary to disperse the uranium in heavy water, that is, in a compound of oxygen and heavy hydrogen (heavy water may be produced from ordinary water by electrolysis. Thus to obtain one liter of heavy water it is necessary to process hundreds of tons of ordinary water, in which the heavy water exists in a state of admixture). Here the oxygen nuclei, for all practical purposes, do not capture the neutrons, because the nuclei of the heavy-hydrogen atoms quickly slow down the speed of the neutrons to the thermal level. The distance traveled by such thermal neutrons through radiouranium seems very small in proportion to the speed of neutrons. However, the growth of the explosion in this case does not proceed fast enough, so the sample mass of radiouranium would fly apart into separate small pieces, without having succeeded in fully exploding. The pieces would be incapable of further explosions because of their small sizes (they are considered small when their linear dimensions are less than the average free path of the neutrons).

Therefore, to bring about explosion of a radiouranium bomb it appears necessary (1) to employ high-speed neutrons with comparatively large free paths and, consequently, (2) to increase correspondingly the geometrical dimensions and, therefore, the weight of the active mass to be exploded. For better utilization of the neutrons, the active mass is surrounded in the bomb by a substance that can reflect the neutrons as strongly as possible. (The physical dimensions of a hard solid mass of radiouranium or plutonium necessary and sufficient for spontaneous explosion can be determined in the following way: Let us assume for the sake of simplicity that all neutrons possess one and the same velocity V to which there corresponds a definite length λ traveled by the average neutrons before its capture by a nucleus. Then each neutrons that appears upon fission of a nucleus causes, by the time $\tau = \frac{\lambda}{v}$, the fission of a new nucleus and thus generates, on the average, γ neutrons. According to Smyth, in the case of radioactive uranium γ equals $1 \sim 3$).

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In the case of (1) an active mass of infinite dimension, and (2) constancy in the number of nuclei capable of fission, then the number of free neutrons should therefore increase, in the time τ, one and a half times. Actually, however, the neutrons located close to the surface of the active mass can escape through the surface and not bring about any fission at all. The number of such lost neutrons flying out through the surface S of the active mass in a certain length of time t that is less in comparison than τ is equal approximately to one half the number of neutrons in a superficial layer of thickness vt (since the other half of the neutrons, if the probabilities of the various directions of travel are all equal, are moving not outwardly but inwardly); that is, the number escaping is equal to the product of $1/2\, vt$ and the number $n = \frac{N}{V}$ of neutrons in a unit of volume of the active mass (where N is the total number of neutrons and V is the volume of the active mass). Then the change in the number N in time t is represented by the difference between the increase $(\gamma - 1) \cdot \frac{Nt}{\tau}$ and the superficial outflow $\frac{1}{2} \frac{N}{V} \cdot Svt$ through the surface. For the chain explosion to progress, it is necessary that this difference possess a positive value. The critical dimensions of the active mass, i.e., the minimum dimensions satisfying these conditions, are expressed therefore by the following:

$$(\gamma - 1) \cdot \frac{Nt}{\tau} = \frac{1}{2} \frac{NS}{V} vt$$

that is:

$$\frac{V}{S} = \frac{v\tau}{2(\gamma - 1)}$$

or, since

$$v\tau = \lambda: \quad \frac{V}{S} = \frac{\lambda}{2(\gamma - 1)} .$$

If the active mass is a sphere of radius R, then $\frac{V}{S} = \frac{R}{3}$, so that the preceding formula takes the form:

$$R = \frac{3\lambda}{2(\gamma - 1)} .$$

In the case of radiouranium, γ is equal to 1 - 3 and therefore $R = \lambda$, i.e., for a spherical radiouranium bomb to explode, its radius must be equal to or greater than the average distance traveled by a fast neutron before its capture.

Later, in the preparation of the atom bomb, American scientists used another principle in producing artificial plutonium. To produce plutonium, at first sight it would seem necessary to bombard uranium with free neutrons from some external source, which would require a great expenditure of energy to free these neutrons from the nuclei holding them, by bombardment with fast protons and deuterons. Actually, however, they succeeded in avoiding this great outlay of energy and also in obtaining plutonium by a process that did not require the use of neutrons from an external source and that was connected, not with the absorption, but with the production of tremendous quantities of atomic energy.

We know that small pieces of ordinary uranium must be distributed in a sufficiently large quantity of heavy water or some other substance, graphite for example, capable of quickly slowing down neutrons without actually capturing them. Secondary neutrons emitted during fission of radiouranium atoms are captured either by other still-undivided atoms of the element (particularly if they have succeeded in losing their speed) or by atoms of heavy uranium U^{238}. In the first case, the neutrons are "multiplied" by the resulting fission of the nuclei of U^{236} [U^{235}?]; in the second, the neutrons result in the formation of super-heavy uranium of atomic weight 239 which thereupon is transformed spontaneously into neptunium and immediately after that into plutonium. To harmonize both processes, it appears necessary to disperse uranium in a moderator (heavy water or graphite) so designed that the neutrons formed inside each piece of uranium are not all slowed down to a low energy level of approximately 25 eV, where neutrons are especially often captured by the heavy isotope U^{238}. The moderator is also so designed that, if neutrons escape one piece with energies considerably greater than 25 eV and then enter the moderator in great numbers, they may strike another piece of uranium as slow thermal neutrons with energies of the order of several hundred eV (which corresponds to the energy of thermal motion at a temperature of several hundred degrees). With rational selection of dimensions for the separate pieces of uranium and also with a sufficiently large graphite-uranium pile (necessary in view of the smallness of the coefficient of increase in the number of free neutrons rising during fission of radiouranium), both processes proceed together in parallel so that the fission of radiouranium does not become an explosion, but progresses comparatively slowly, leading finally to the transformation of a small part of the heavy uranium to plutonium (in quantities approximately equal to the amount of the light isotope). The nuclear energy released during this process (i.e., the kinetic energy of products of fission of U^{235} and also beta radiations emitted during the conversion of U^{239} into neptunium and later into plutonium) may be utilized to power various mechanisms and machines for peaceful industrial purposes.

According to official American data, this course has seemed the most rational and economical one to pursue during the production of plutonium for atom bombs (each bomb contains several kilograms of plutonium). In the moderator, graphite carefully freed of admixtures capable of capturing neutrons was generally used. This work was directed by E. Fermi and was crowned with success. Uranium was then introduced into this graphite mass in the form of thin rods, so that they formed a lattice-like mass inside. After the preparation of plutonium, the latter can be separated by ordinary chemical methods in the form of small crystals incapable of spontaneous explosions, especially in consequence of their small dimensions.

The ability or inability of a piece of radiouranium or plutonium to explode spontaneously, depending on its geometrical dimensions, is related to the fact that part of the neutrons appearing within these pieces can escape outwardly without encountering any collisions and then completely disappear; that is, these escaping neutrons are incapable of further multiplication of free neutrons. The greater the relative number of such escaping neutrons, the greater must be the surface of the piece under consideration in ratio to its volume. If this piece is spherical, then the ratio of surface to volume is inversely proportional to its radius.

If the radius is large in comparison with the average distance traveled by a neutron before capture, then the leakage of the neutrons through the surface does not play an essential role. In this case the avalanche of neutrons develops quickly and finally effects an explosion. If the radius is small in comparison with the distance traveled by a neutron before capture, then the occurrence of such an avalanche becomes impossible. The critical value of the radius at which the metal ball of radiouranium or plutonium loses stability is close to the average distance traveled by a neutron before final capture, depending upon the active mass and the speed of neutrons.

To prevent the spontaneous explosion of radiouranium or plutonium it is necessary to prepare and maintain these substances in the form of separate pieces of so-called "pre-critical," i.e., close to the critical size. The union of two or more such pieces into one so-called "hypercritical" piece must lead to instantaneous explosion. The explosion of an atom bomb is effected in this manner.

This explosion is propagated within the bomb with tremendous speed, close to the speed of motion of neutrons. If this motion possesses a speed of the order of 1/10 or 1/100 that of light, then the explosion outruns the process accompanying it, that of breaking up or vaporizing the solid substance comprising the bomb's active mass. This process more or less guarantees the fully efficient utilization of the precious mass.

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This situation in particular clearly explains the inexpediency of slowing down the neutrons by dispersing or diluting the radiouranium or plutonium in heavy water or in graphite: the decrease, otherwise desirable, in the minimum quantity of these substances (radiouranium or plutonium) necessary for explosion (in connection with the decrease in the average distance traveled by a neutron before capture) does not compensate for this decrease in the effectiveness of explosion, i.e., the actual effective nuclear explosion is of too short a duration. It is possible, however, that the variation in such dispersal of the active mass may prove very expedient when utilizing atomic energy for industrial purposes.

To utilize for peaceful nonmilitary purposes the elemental explosive substances which all heavy elements (above all, radioactive uranium and plutonium) seem to be, it is necessary for physicists and engineers to learn to control the processes of these substances, not permitting sudden violent explosions but guaranteeing a comparatively slow flow of energy, released in a smooth controlled manner as desired and not in powerful explosions reducing everything to ashes. (As for the magnitude of destruction produced by atom bombs which were hurled on the Japanese ports of Hiroshima and Nagasaki, we have sufficiently detailed information obtained from foreign publications. In this connection, we consider the following worthy of note: the fear that the explosion of an atom bomb can explode the surrounding matter and almost all the world is absolutely ridiculous since the earth and particularly its crust consists mainly of light elements fully stable relative to the processes of nuclear fission and disintegration.)

The danger of the transition from the slow burning of fuel in furnaces or motors to the terrible nuclear explosion is prevented by various methods: by systems of supplying fuel and burning it and also by the introduction of various antidetonators or similar substances to slow down the growth of the burning reaction. A similar problem of controlling nuclear reaction on the industrial scale confronts the new sciences of atomic physics and technology. This problem, though very complicated, is fully solved, but obviously it is still impossible to reveal the concrete methods of its solution.

If science and technology succeed in checking the impetuous growth of nuclear "firebrands" by some sort of nuclear reaction involving the condensation of hydrogen into heavier elements or the disintegration of heavy elements, to absorb excessive energies of nuclear reactions, then a new era will open up before humanity, that of the complete domination of the forces of nature dormant in inert matter. These forces are the ones which were not completely spent during the period of development of matter in the centers of stars. They permit mankind not only to guarantee well-being on the earth but also, perhaps, empower him to realize the dream of interplanetary travel. The utilization of atomic energy for the good of mankind seems, however, to be possible only if it concerns not only physicists and technologists, but also harmonious diplomatic relations between the various nations and states.

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